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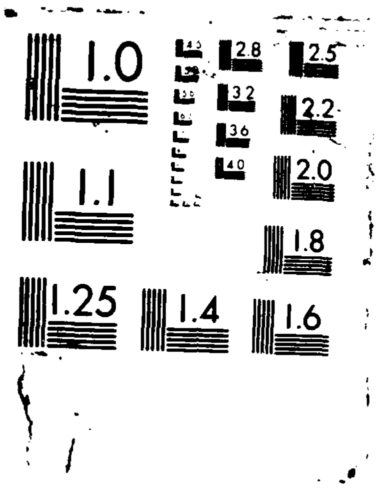
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Sounds produced by acoustic sources are localized and detected on the basis of differences in the time of arrival between the two ears and differences in the levels at the two ears. Most real-world sounds are spectrally complex, consisting of energy distributed across many frequencies. In general, the auditory system must make judgments regarding the location of acoustic sources on the basis of these interaural differences, even though their distribution across frequency may be quite complex. This proposal has sought to understand the processes by which the binaural auditory system combines interaural information across the spectrum. The auditory system is spectrally synthetic, averaging information across the frequency domain, when the signal consists of relatively few components. Under these circumstances, the system behaves as though all components arise from the same spatial location. When the stimulus consists of many components the system is spectrally analytic, so that frequency components whose interaural parameters are different are "heard out."

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The theme of our grant was localization of complex sounds. A variety of studies were conducted on that topic, but also on topics related to the general area of binaural processing and the area of complex sound processing. In the first section of this Progress Report we provide brief abstracts of some of the work on basic binaural processing. These studies continue to provide some of the basic information concerning binaural processing which we used in our direct studies of the binaural processing of complex sounds.

BASIC BINAURAL PROCESSING

The Precedence Effect: Revisited

William A. Yost and David R. Soderquist

The precedence effect, as investigated by Wallach et al. [Am. J. Psychol. 62, 324-336 (1949)] was studied in three experiments. Experiment I was a replication of the original work of Wallach et al. Although the first click pair appears to dominate the perception of the position of the lateral image, the effect of the first click pair does not appear to "offset" or "cancel" the effect of the second click pair in terms of producing a lateral image at midline. The data are consistent with Zurek's [J. Acoust. Soc. Am 67, 952-964 (1980)] proposal that the binaural system is less sensitive to the interaural temporal difference of the second click pair. Experiment II indicated that the effect of the first click pair on lateral judgments still dominates that of the second click pair when the images are judged to be off midline. In all of these studies, the variability of the data is quite high. Experiment III showed that the first click pair also led to a larger change in masked thresholds (masking-level differences, MLDs) than does the second click pair. These data reconfirm the use of two-click stimuli for demonstrations of the precedence effect and they describe some of the limitations of the procedure and the generalities of the effect.

Click Stimuli Do Produce Masking-Level Differences, Sometimes
William A. Yost

In recent years some investigators have presented data indicating that click stimuli do not always produce Masking-Level Difference (MLD). These studies have implied that MLDs may not occur for clicks in the same way that MLDs occur for tones. This contrasts with the older literature which showed that MLDs are obtained with click stimuli for approximately the same conditions as those used to obtain MLDs for tonal stimuli. This research brief describes an attempt to discover the reasons for the discrepancies among these studies. In the simultaneous-masking condition varying the click location relative to masker onset resulted in very little change in click threshold. There was also very little between-subject variability (standard error of the mean across all conditions and subjects was 2.2 dB). Thus, the data were averaged across listener and across the three temporal locations of the click relative to masker onset. In the forward-masking conditions two listeners (S1 and S2) performed similarly. The third listener (S3) had similar thresholds to S1 and S2 in the NoSo conditions, but higher thresholds in the NoS|| condition. The click thresholds in the NoSo condition are used to estimate the amount of masking in each condition. The parameter in each figure is the cutoff frequency of the low-pass filter for the click. Each numbered data point represents a different condition as indicated in the legend. The data clearly show that the MLD is proportional to the level of the masking noise. The slope of the function is approximately 0.2 dB increase in the MLD for each decibel increase in masker level for the 1500-Hz low-pass click and a lower slope of approximately 0.13 for the 5000-Hz low-pass click. The results of this study suggest that MLDs for click stimuli depend on masker level in approximately the same way that the MLDs for tonal stimuli depend on masker level. In forward masking, the results of this study suggest that between-subject variability might be a significant contributor to differences observed in the literature in the size of the MLD for click stimuli.

Prior Stimulation and the Masking-Level Difference
William A. Yost

Signal detection in diotic (NoSo) and dichotic (NoSπ) conditions was measured as a function of the stimulus parameters of the noise that preceded the signal-plus-masker. When the signal and masker were both pulsed, dichotic signal detection was worse than when the masker was continuous or when the onset of the masker preceded the signal-plus-masker by at least 500 ms. The dichotic detection thresholds decreased as the duration of the pulsed signal plus pulsed masker was increased. The level, spectrum, interaural configuration, duration, and temporal proximity of the prior noise (forward fringe) relative to the masker and/or signal and masker were all investigated. Almost any difference between the parameters of the fringe and the masker resulted in poorer signal detection in the dichotic conditions. These same stimulus conditions produced small (less than 2.2 dB) changes in the diotic detection thresholds. The various models of the Masking-Level Difference (MLD) may be modified to qualitatively describe some of these results.

Masking-Level Differences for Trains of Clicks
Raymond H. Dye and William A. Yost

Masking-level differences (MLDs) were measured for trains of 2000-Hz bandpass clicks as a function of the interclick interval (ICI) and the number of clicks in the train. The magnitude of the MLD grew as the number of clicks in the train was increased from 1 to 32. While the MLDs tended to be larger at longer ICIs, the effect was mediated by changes in detectability in the homophasic conditions. For click trains consisting of 4-32 clicks, the improvement in detectability in the antiphasic conditions with increases in the number of clicks appears to be the result of integration of acoustic power, as is the case for the homophasic conditions. The absence of MLDs for short trains of high-frequency transients remains quite puzzling, since large MLDs are found with single, low-frequency transients.

Discrimination of Interaural Differences of Level as a Function of Frequency
William A. Yost and Raymond H. Dye, Jr.

Discrimination of interaural differences of level (IDLs) was measured for pure tones as a function of frequency and as a function of the interaural difference of phase or level of a standard. Varying the interaural difference of the standard was assumed to change the lateral position of its intracranial image. Threshold IDLs were approximately constant over a frequency range from 200 to 5000 Hz, except in a region near 1000 Hz where they were slightly elevated. Thresholds increased as the value of the standard interaural differences of phase or level increased, implying that interaural resolution declines as the lateral image moves away from midline. The results are generally consistent with the predictions of current models of lateralization, but additions to these models are required in order for them to account for the slight frequency-dependence of threshold IDLs.

Lateralization: A Comparison of Five Psychophysical Procedures
J. N. Baumann, R. H. Dye, and W. A. Yost

The lateralization performance of two subjects was compared across five psychophysical procedures. The procedures used were single interval, same-different (SD), 2-interval forced choice, 4-interval SD, and 4-interval 2AFC. Psychometric functions were determined for each procedure by measuring d′ for phase differences of 2, 4, and 6 degrees (interaural time differences of 11, 22, and 33 μsec). The stimuli were 500-Hz tones of 250-msec duration, presented at 70 dB SPL. In order to facilitate comparison, d′ was not corrected for number of observation intervals, so that ratios of d′ could be formed and compared to those predicted by the Theory of Signal Detection (TSD). In general, performance was found to be superior with the 4-interval 2AFC task and worst with the single interval task. Differences between the psychometric functions produced with four-interval tasks and the single-interval task were larger than predicted by

TSD. These discrepancies are discussed in terms of additional cues for motion and location provided by the four-interval tasks.

Masking-Level Differences as a Function of Masker Level: Revisited.
William A. Yost

Measurement of the masking-level difference (MLD) has been suggested as a possible test for some types of hearing disorders. When MLDs are measured with hearing impaired patients careful attention must be paid to the overall stimulus level and differences in sensitivity between the two ears. As a consequence, new studies of the MLD have been reported in which either overall masker level or interaural differences in masker level have been investigated. Studies done in the late 1960's proposed an explanation for the dependence of the magnitude of the MLD on masker level or interaural differences in masker level. In general, this explanation assumes that additive internal noise present in the outer ear produces a significant contribution to the masking stimulus at the low signal frequencies typically used in studies of the MLD. The present paper will review this explanation and combine it with the predictions of the Durlach Equalization-Cancellation Model of binaural analysis to fit the data from all of the studies since 1948 that have investigated the MLD as a function of masker level or interaural masker level. The fit to these data is excellent. In addition, data from a study using insert headphones will be described. The use of insert headphones, instead of the supra-aural headphones typically used to measure the MLD, should reduce the contribution to the masker of the additive internal noise present in the outer ear.

AUDITORY PROCESSING OF COMPLEX SOUNDS

We also have continued our studies of complex sounds, especially those complex sounds which provide a strong sensation of pitch. These studies have looked at the temporal characteristics of rippled noise and the use of lateral inhibitory mechanisms to describe the processing of many complex sounds.

Temporal Changes in a Complex Spectral Profile
William A. Yost and M. J. Moore

The spectral properties of a complex stimulus (rippled noise) were varied over time and listeners were asked to discriminate between this stimulus and a flat-spectrum, stationary noise. The spacing between the spectral peaks of rippled noise was changed sinusoidally as a function of time, or the location of the spectral peaks of rippled noise was moved up and down the spectrum as a sinusoidal function of time. In most conditions listeners were able to make the discriminations up to rates of temporal modulation of 5 to 10 cycles per second. Beyond

5-10 cps the rippled noise with the temporally varying peaks was indiscriminable from a flat (non-rippled) noise. The results suggest that for temporal changes in the spectral peaks of rippled noise, listeners cannot monitor the output of a single (or small number) of auditory channels (critical bands), or that the mechanism used to extract the perceptual information from these stimuli is slow. Temporal variations in the spectral properties of rippled noise may relate to temporal changes in the repetition pitch of complex sounds, the temporal properties of the coloration added to sound in a reverberant environment, and the nature of spectral peak changes such as those that occur in speech-formant transitions. The results are relevant to the general issue of the auditory system's ability to extract information from a complex spectral profile.

This paper forms one of the motivations for some of the research described in the present proposal. The inability of subjects to process time-varying rippled noise at rates above 5-10 cycles per second suggests (as discussed in the paper by Yost and Moore, 1987) a spectral integration of temporal information across many critical bands. The concept of spectral integration of temporal information is a theme pursued in the present proposal.

Processing of Complex Signals and the Role of Inhibition
William A. Yost

Most recent models of pitch perception assume that pitch information is extracted from a pattern of spectral activity existing at the output of the peripheral auditory system. The spectral pattern results from comparing the outputs of many frequency channels, which are usually modeled as critical band or neural-tuning curve filters. By using weighting functions with areas of suppression, instead of the traditional critical band filters, spectral patterns with heightened regions of activity are produced. We have described the use of suppression to heighten certain regions in a spectral pattern. These heightened regions of activity are used to account for such phenomena as the spectral dominance region for pitch, the pitch of inharmonic complexes, and pitch strength. We also consider the possible use of suppression and the resulting spectral patterns to account for auditory perception of a variety of complex, non-speech stimuli, including speech signals and those signals used to study 'profile analysis.'

Auditory Processing of Complex Sounds (A Workshop and Book)
William A. Yost and Charles S. Watson

A major undertaking during this grant period was the organization of the workshop on 'Auditory Processing of Complex Sound' help in April 1986 and the publishing of the book by the same title in 1987. The major findings of that workshop and book are explained in the Introductory chapter to the book written by Yost and Watson, the co-chairs of the workshop and co-editors of the book. One of the interesting findings of the workshop was the role temporal modulation plays in processing complex sounds. The research described at the Workshop, in the book, and the discussions at the workshop were partially responsible for many of the ideas proposed in this grant application.

BINAURAL PROCESSING OF COMPLEX SOUNDS (Large Number of Spectral Components)

A major observation deriving from our studies of binaural processing of complex sounds is the difference in modes of processing between stimuli with a small number of spectral components (fewer than 10) and stimuli with a large number of spectral components (more than 1000). Stimuli with a small number of components appear to be binaurally processed in a synthetic mode while stimuli with a large number of components are processed in an analytic mode. The stimuli we have used to investigate binaural processing of complex sounds with many components have been different versions of the Cramer-Huggins binaural pitch stimuli. A large study on the perception of these stimuli was reported on in the book, Auditory Processing of Complex Sounds (edited by Yost and Watson, 1987):

Complex Spectral Patterns with Interaural Differences: Dichotic Pitch and the 'Central Spectrum' William A. Yost, P.J. Harder, and R.H. Dye

A complex sound's amplitude and phase spectra are likely to be different at one ear relative to the other ear when the sound arrives at the two ears. This work describes experiments involving broadband stimuli in which narrow bands are presented with interaural differences of amplitude or phase. Listeners perceive a pitch for these stimuli that corresponds to the spectral location of the band of interaurally shifted components. These stimuli produce a version of the Cramer-Huggins dichotic pitch. A psychophysical procedure was developed to estimate the salience of the dichotic pitches for a variety of stimulus conditions. The results are described in terms of a 'Central Spectrum' and are discussed in relationship to conditions that yield binaural masking-level differences (BMLD).

Figure 1. Three dimensional plots indicating the number of reported pitches as a function of the center frequency of the band of noise with an interaural shift and as a function of the amount of phase shift or level difference. Pitches in the region of 200-1500 Hz are the most salient.

BINAURAL PROCESSING OF COMPLEX SOUNDS (Small Numbers of Spectral Components)

The Combination of Interaural Information across Frequencies: Lateralization on the Basis of Interaural Differences of Time for Three-component Complexes. Raymond H. Dye

In this study, threshold interaural differences of time

(IDTs) were measured for three-component stimuli in which one, two, or all three components were interaurally delayed. The center frequency of the complex was always 750 Hz, and thresholds were measured for frequency separations of 20, 50, 100, 250, and 450 Hz. For comparison, thresholds were also measured for each of the frequencies that were constituents of the complexes. The components were all 73 dB SPL. Thresholds were measured with a 2-alternative forced choice task in which the delay was to one ear during one interval and to the other ear during the other interval (producing left-right or right-left movement of intracranial images).

Figure 2 shows the data for two subjects. The first three labels on the X-axis designate conditions for which single components were presented (low, middle, or high). The next three designate conditions in which all three components were presented but only one was delayed (L, M, or H), and the next three labels refer to conditions in which two of the three components were delayed. Finally, the last label shows thresholds when all three components were delayed ("waveform delay").

The most striking feature of these data is the large effect of the presence of diotic components, especially for cases in which only one of the three components was delayed (compare L, M, and H with 3L, 3M, and 3H). The interference imparted by the diotic components was greatest when the middle component (750 Hz) was the only delayed one, except when the frequency separation was rather large and the binaural system grew increasingly insensitive to the low-frequency component of the complex (note that the highest threshold for 300-750-1200 is obtained for 3L rather than 3M).

Interestingly, the deleterious effects of diotic components were observed at all frequency separations at which thresholds were measured. While the elevation of thresholds was generally greater for small frequency separations, thresholds for conditions in which one component was delayed were elevated even for separations of 250 and 450 Hz. These data suggest the presence of binaural integration across ranges of frequency that far exceed the critical band.

When observers were asked to report their impressions of the intracranial images formed by three-component stimuli with diotic components, they indicated that a single image was heard (rather than a moving dichotic component and stationary diotic components at the midline). This phenomenological observation was generally borne out in a second experiment in which two of the three components were fixed with an IDT of 25 μs, while the other--the incoherent component--was delayed in the opposite direction by varying amounts. These data are shown in figure 3 for subjects SS and RS. For small delays of the incoherent component, lateralization tends to be "driven" by the coherent components. For larger delays of the incoherent component, lateralization tends to be driven by the incoherent components. For most cases, the % response to the coherent components ranges from 0 to 100%, indicating that some sort of "trading" across frequencies occurs. This is true even for frequency separations of 250 Hz. Functions that lie to the left indicate that those components are "weaker" in determining lateral position, since larger delays are required to offset the 25 μs delay in the coherent components. Interestingly, the positioning of the three functions in each panel generally predicts, at least qualitatively, the ordering of interaural thresholds obtained for these two subjects in the previous study. Even the intersubject differences obtained in the threshold study tend to be predicted from these left-right judgements. Note that subject SS was least sensitive to 3L for 500-750-1000 Hz, while RS was least sensitive to 3M. The relative strengths of these components, as measured by left-right judgements for complexes whose components oppose one another, are also reversed for these two subjects.

The Combination of Interaural Information across Frequency: The Effects of Phase-randomization on the Detection of Interaural Differences of Time in Five-component Complexes. Raymond H. Dye.

In order to obtain a clearer picture of the way in which diotic components impede the detection of those that have been interaurally delayed, threshold IDTs were measured for complexes consisting of 550-650-750-850-950 Hz. Furthermore, comparisons were made between thresholds measured when all components were added in sine-phase and those obtained when the starting phases were randomized between intervals of the two-interval task. The aim in doing so was to test the hypothesis that the deleterious effects of adding diotic components in the previous study were due to alterations of the temporal waveform rather than interactions across critical bands. Systematic effects of interaural configuration were only found for conditions in which one of the five components was delayed (thresholds were somewhat smaller for conditions when the delayed component is the lowest or highest frequency in the complex). Furthermore, the effect of starting-phase appears to be minimal, with only the **m**=1 thresholds substantially elevated by phase-randomization.

Figure 4 shows thresholds as a function of the number of delayed components (collapsed across interaural configuration). The optimal stategy for the observer would be to take independent estimates of the IDT at each of the five frequencies. From the Theory of Signal Detectability, one would expect dectectability to obey $d'^2_m = \sum_{i=1}^{m} d'^2_i$, where **m** is the number of delayed components. As such, perfect integration of interaural information predicts d' to increase by $\sqrt{m}$ and threshold to fall by $\sqrt{m}$ if sensitivity to the individual components, presented in isolation, was the same (the n-m diotic components would have no impact of detection). Instead of finding the predicted slope of -0.5 (in logarithmic coordinates), the slope is nearly -1.0. The rapid decline in threshold with number of delayed components reflects the fact that d'_m appears to be a weighted average of the d's of the individual components **including** those for which d'=0.0.:

$$d'_{m/n} = \frac{md'_1 + (n-m)0.0}{n},$$

where $\mathbf{d'_1}$ is the d' of the individual components in isolation (assumed to be the same), **m** is the number of delayed components, and **n** is the total number of components.

These data, like those discussed above, indicate an integration of interaural information across frequencies--in no condition are subjects able to "ignore" diotic components, even when distant components fall outside of critical bandwidths. They also support the contention that the deleterious effects of adding diotic components are not the result of alterations of the temporal waveform.

The Combination of Interaural Information across Frequencies: Masking-level Differences for Three-component Complexes.
Raymond H. Dye and William A. Yost

In this study, the effects of frequency incoherence in the signal on the ability of observers to detect signals in a background of noise. As a start, we have measured the detectability of 3-component complexes as a function of the number of interaurally phase-reversed components, which of the components were antiphasic, and the frequency spacing of the components.

The center frequency of the complex was always 750 Hz, and the frequency separation was 250, 100, or 20 Hz. The durations of the signals were 100 ms, with linear onset/offset ramps of 10 ms. Signals were presented against a continuous low-pass noise (2.5-kHz cut off frequency, 48 dB/oct slopes) whose spectrum level was 42 dB. The levels of the three components were equal, and the level of the individual components was used to define the level of the complex rather than total power. Psychometric functions were measured for each condition, and thresholds were defined as the E/No's necessary for d'=1.0 defined by least squares fits in log-d' log E/No space. The task was 2-alternative forced-choice.

For comparison to MLDs measured with 100% amplitude modulated sinusoids, the waveforms used in this study are analagous to SAM with a modulation index of 2.0. The π, π, π conditions are like those of carrier delay (1/2 the carrier period) and π, 0, π conditions are like those of modulation delay (1/2 the period of modulation). The difference, however, is that this study measured MLDs at all other interaural configurations.

Figure 5 shows psychometric functions for frequency separations of 250, 100, and 20 Hz. Conditions where 2 of the 3 components were antiphasic are omitted here so that one can more clearly see the effects of the presence of 2 diotic components. The first panel shows data for 500-750-1000 Hz. On the right we see functions for the individual frequencies that comprise the complex, with ○ = the low frequency sideband, △ = the carrier frequency, and ◇ = the high frequency sideband. The closed symbols with solid lines show the data for single antiphasic tones. The open symbols with solid lines depict the data when all three components are present in the signal, but only the low (●), middle (▶), or high (◆) frequency component is antiphasic. Note that detectability is best when all three components are delayed, but that the presence of diotic components 250 Hz or more from the antiphasic component degrades performance (at least for 500 and 750 Hz). Note that the data from the two subjects are quite similar, except that the second subject shows a larger frequency-dependence for the detection of antiphasic signals.

The next panel shows data for 650-750-850 Hz, with the same hierarchy of detectability as a function of frequency. Only the performance of the second observer was superior in the pure tone dichotic conditions (compared to cases in which the same component was antiphasic within complexes).

As the separation in frequency is moved to 20 Hz (right panel), the dichotic conditions tend to collapse, with superior performance still obtained when all three components are antiphasic. Diotic performance when 3 components were present improves by 4-5 dB, as one would expect on the basis of total power.

For small frequency separations, the question arises as to what diotic reference one might use in defining a masking level difference, and it is this problem that necessitates the presentation of psychometric functions. For separations of 100 and 250 Hz, the issue is not as important because diotic detection is no better with 3 components than with pure tones. The presence of diotic components in the three-component complexes reduces the magnitudes of the masking level differences, even when the frequency separations are as large as 250 Hz. The MLDs obtained when two of the three components are antiphasic are nearly as large as when all three are interaurally phase-reversed, especially when one of the antiphasic components is the lowest frequency component of the complex (see panels 1 and 2). While the differences between L and 3L, M and 3M, and H and 3H for the data gathered at 730-750-770 Hz are difficult to interpret because they are referenced to different diotic conditions, there is a consistent growth in the MLD as the number of dichotic components is increased.

Models of binaural hearing have generally held that a central processor ("cross correlator") operates on the outputs of critical band filters of the left and right ears that are tuned to the same frequency. The picture that emerges from these data and those from studies of the lateralization of multi-tonal complexes is one of integration across frequency ranges that are far wider than the critical bandwidth.

The Law of the First Wavefront: The Effect of Spectral Differences Between Initial and Subsequent Acoustic Events.
Raymond H. Dye and Steve Doran.

An investigation is in progress to examine the range of frequency differences between initial auditory events and those that follow over which the precedence effect can be obtained. To this end, observers are asked to make judgments regarding the direction of apparent movement of trains of Gaussian clicks for conditions in which the first click leads in time to one ear and the subsequent clicks lead to the other ear. The spectrum of the first click iss centered at 4000 Hz and leads in one ear by 56, 136, or 216 us. The subsequent click(s) is centered at 3500, 3900, 4000, 4100, or 4500 Hz, and delayed to the opposite ear by a variable amount. The signs of IDT_1 and IDT_2 are reversed between intervals of the two interval task, so images appear to move from left to right or from right to left. The number of clicks in the train is 2 or 4. The interclick interval at one ear is 5 ms, while at the other interval it is 5 ms-IDT_1-IDT_2. These values may seem relatively long for a study of precedence, but they are sufficiently short for the precedence effect to be in evidence (Zurek, 1980) and sufficiently long that the magnitudes and signs of differences of time and intensity between the two ears, when the spectra of the entire trains are considered, change rapidly as a function of frequency. This prevents listeners from performing the task by restricting attention to spectral regions where time and intensity differences are reinforcing (Gaskell, 1983).

Initial findings show that the first click is more important in determining the laterality of the intracranial image than are subsequent ones, even when there are substantial differences between the center frequencies of the clicks. Only when the center frequency of clicks 2-N was 3500 Hz was there evidence for a loss in the dominance of the first click over later ones. Similar measurements are being taken for larger spectral disparities between $click_1$ and $clicks_{2-N}$.

Discrimination of Tonal Complexes on the Basis of Which Component is Interaurally Delayed. Raymond H. Dye, Jr.

The question addressed in this experiment concerns the extent to which human observers have access to information regarding which frequencies in a complex are interaurally delayed. A discrimination experiment was performed in which subjects had to discriminate between 3-component waveforms in which one component was interaurally delayed during one interval and another was interaurally delayed during the other interval. The right ear always received the signal with the delayed component, so the images were always lateralized to the left. The three components were 653, 753, and 853 Hz, so the discriminations to be made were between (a) 653_T-753-853 and 653-753-853_T, (b) 653_T-753-853 and 653-753-853_T, and (c) 653-753_T-853 and 653-753-853_T. Similar conditions were run with a 200-Hz spacing (553-753-953 Hz). Performance in the above conditions was measured in units of d' (discrimination d's). In addition, functions relating d' to IDT were measured for each of the possible components in the complex (versus a diotic 3-component complex). These are referred to as interaural-time detection d's. Typically d's were measured as a function of the delay of the higher-frequency component for three different values of the IDT of the lower component. The signals were 200 ms in duration, gated with 20-ms linear rise decay times. Each component was presented at about 50 dB SPL. In order to assure that subjects did not make discriminations based on posssible differences in the qualities of the temporal waveforms arising from delaying different components, the starting phases of each component in the complex were randomized between intervals of a two-interval task.

The variety of possible decision stategies available to the subjects required that care be given in the explanation of how subjects were to make responses in this task. First, subjects were instructed to respond by pressing the leftmost lever if the higher-pitched component was laterally displaced during the first interval and the rightmost lever if it was displaced dring the second interval. Secondly, subjects were informed that, should they be unable to determine pitch differences between the lateralized images, to respond with the rightmost lever if the images appeared to move to the right across the two intervals and the leftmost lever if they appeared to move leftward. If observers have knowledge regarding the frequency of the lateralized components, d's were expected to be positive regardless of the values of the interaural delays. Furthermore, the d's should increase as the interaural difference of time for either of the delayed components is increases. On the other hand, negative d's reflect the fact that the complex containing the delay in the lower frequency component was lateralized further to the left than the one containing delay in the higher frequency component, with subjects unable to identify which component had been interaurally delayed.

The results are presented for one subject (Figure 6) in the figure below, where d' is plotted as a function of the delay of the higher frequency. The data show that d's go negative when the magnitude of $IDT_{low\ freq.}$ is much greater than $IDT_{high\ freq.}$, and this result is obtained for most conditions where it is predicted. Furthermore, d' is reduced as $IDT_{low\ freq.}$ is increased. This outcome is inconsistent with a discrimination process based upon independent sampling of interaural delay at the two frequencies. Interestingly, all subjects report that they make discriminations based on the relative movement of the complexes, with no subject reporting separate movement of individual components. These results are generally consistent with the contention that human observers do not have access to information regarding which component in three-tone complexes is interaurally delayed. Although there are many well-documented situations in which the binauaral auditory system can perform in a frequency analytic manner (e.g., the extraction of Huggins-Cramer pitch), it appears that the system is frequency synthetic when the stimulus is restricted to a relatively small number of components.

The Contribution of Sidebands in the Detection of Interaural Envelope Delays for Five-component Complexes. Raymond H. Dye, Jr. and Andrew Niemiec.

In this study, threshold interaural differences of time (ΔIDT) between the envelopes of high-frequency waveforms were measured as a function of the modulation rate (20, 50, 100, 200, 250, 300, 400, and 500 Hz) for both 3- and 5-component complexes whose center frequency (f_c) was either 2000 or 4000 Hz. To create an interaural envelope delay, the phase of each component at the delayed ear relative to the other ear is given by

$2\pi(IDT)(f_c - f)$: components lower than the carrier lead while those above the carrier lag in phase. For three-component complexes, the components present in the stimulus are given by $f_c - f_m$, f_c, and $f_c + f_m$, while for five-component complexes the stimulus consists of these three in addition to $f_c - 2f_m$ and $f_c + 2f_m$. A two-interval, forced-choice task was used in which the envelope lagged to the right ear during one interval and lagged to the left ear during the other interval. As such, the stimuli, which were presented through headphones, either appeared to move from left to right or from right to left. The level of each component was 50 dB SPL, and the total duration of each stimulus interval was 200 ms with 10-ms linear rise-decay times. Threshold envelope delays were estimated from 3- or 4- point psychometric functions by linear interpolation to determine the delays yielding d's of 1.0.

The goal of this experiment was to assess the contribution of the outer two components for the detection of envelope delays for five component complexes. As a first step, a comparison was made between thresholds obtained for three- and five-component stimuli. The results showed no apparent effect of the number of components regardless of the modulation frequency, arguing that the outermost sidebands provided little aid to lateralization. The only exception occurred when the center frequency was 2000 Hz and the modulation rates were large, in which case performance with 5-component complexes was poorer than with 3-component complexes. This difference arose because sensitivity to interaural delay at the lowest component (which is advanced when the envelope is delayed) markedly impedes ones ability to utilize envelope delays, and this problem is more prevalent for 5-component complexes since there is more sensitivity to interaural differences of time for their lowest-frequency components than for the lowest sidebands of 3-component complexes.

These findings seemed consistent with the notion that the envelope is extracted from components interacting within an auditory filter, with more distal components having no effect. A strong prediction from such an assertion is that the interaural phase of the outermost sidebands, $f_c - 2f_m$ and $f_c + 2f_m$ should have no effect upon the ability to lateralize five-component complexes on the basis of an envelope delay generated by interactions between the middle three components, especially at high modulation rates where the outermost sidebands are remote. Surprisingly, making the outermost sidebands diotic was found to <u>severely</u> impare one's ability to utilize interaural envelope delays contained in the middle three components, even when the modulation rates were quite high (and the outermost sidebands should fall into different auditory filters than the middle three components). These findings place in doubt the contention that the binaural auditory extracts envelopes by monitoring the outputs of narrowband auditory channels.

A Comparison of the Effects of the Phase Randomization and Decreasing Modulation Depth on the Detection of Interaural Envelope Delays. Raymond H. Dye and William A. Yost.

When identical high-frequency carriers are presented to the two ears but the sinusoidal amplitude modulator is delayed to one ear relative to the other, the delay of the modulator can be a potent cue for lateralization. In this experiment, the effects on performance of randomizing the starting phases of components and decreasing depth of modulation of waveformwas qualitatively assessed. The carrier frequency was either 2000 or 4000 Hz, and the modulation frequency was fixed at 200 Hz. Performance (d') was measured as a function of the depth of modulation (0.25, 0.50, 0.75, and 1.0) and the interaural envelope delay. As has been found elsewhere (e.g., Nuetzel and Hafter, 1976; Henning, 1974), reducing the depth of modulation severely impedes one's ability to lateralize these SAM waveforms. On the other hand, randomization of the starting phases the components has virtually no effect upon performance, yet phase-randomization, like decreasing modulation depth, reduces the peak-factor of the waveform. The most parsimonious explanation for these data is that the envelope-extraction mechanism operates in a component-by-component manner so that the starting phases of each component become irrelevant.

Recently efforts have been put forth to develope algorithms to control (usually limit) the peak-factor (the difference between the maximum and minimum amplitudes divided by the rms value) of signals (Schroeder, 1970; Pumplin, 1985). Currently we planning to measure sensitivity to interaural envelope delays for SAM and phase-randomized waveforms having comparable peak-factors.

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Supported Presentations:

Dye, Raymond H. Jr. Discrimination of Tonal Complexes on the Basis of Which Component is Interaurally Delayed. Paper presented at the meeting of the Acoustical Society of America, Anaheim, 1986.

Yost, William A. Two Ears, One World, Symposium, Colorado College, Colorado Springs, 1986

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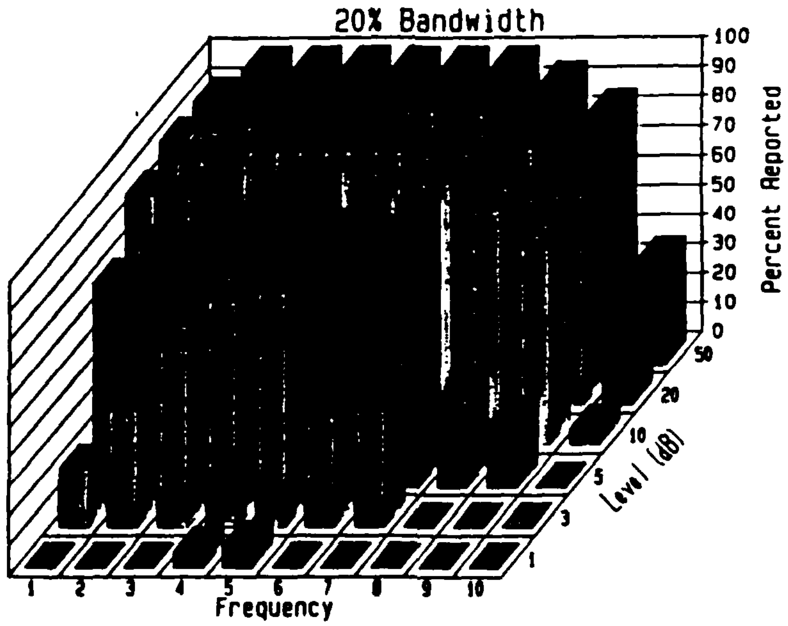
Fig 1



	20%		
	Lo	C	Hi
1	199-	221-	243
2	275-	305-	336
3	380-	421-	464
4	525-	582-	641
5	725-	803-	885
6	1001-	1110-	1222
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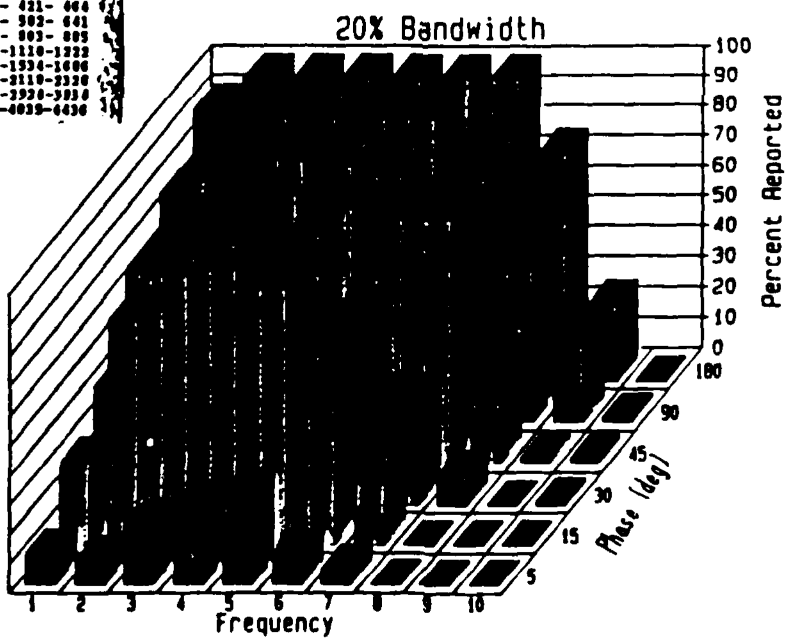


Fig 2

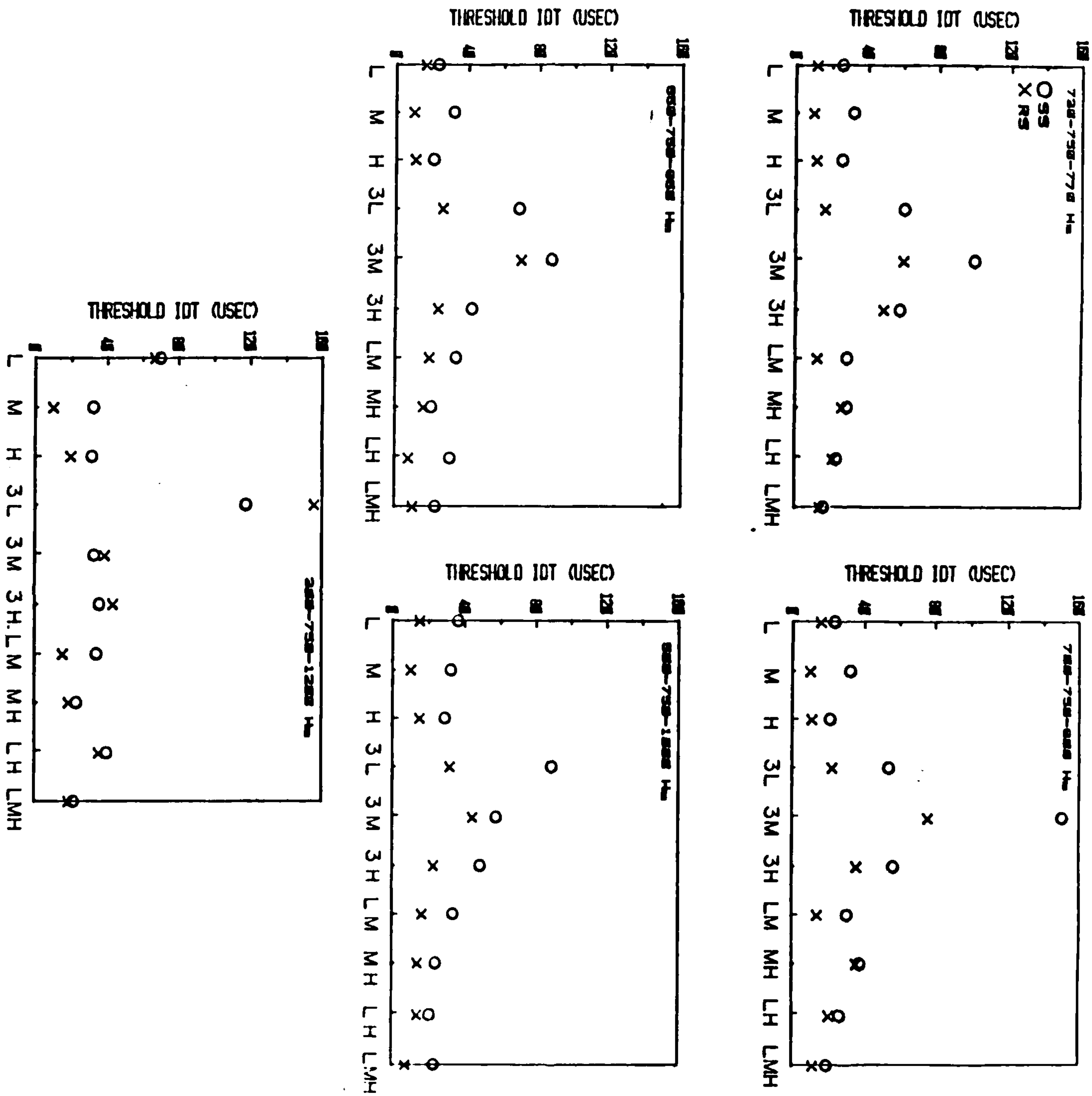


Fig 3

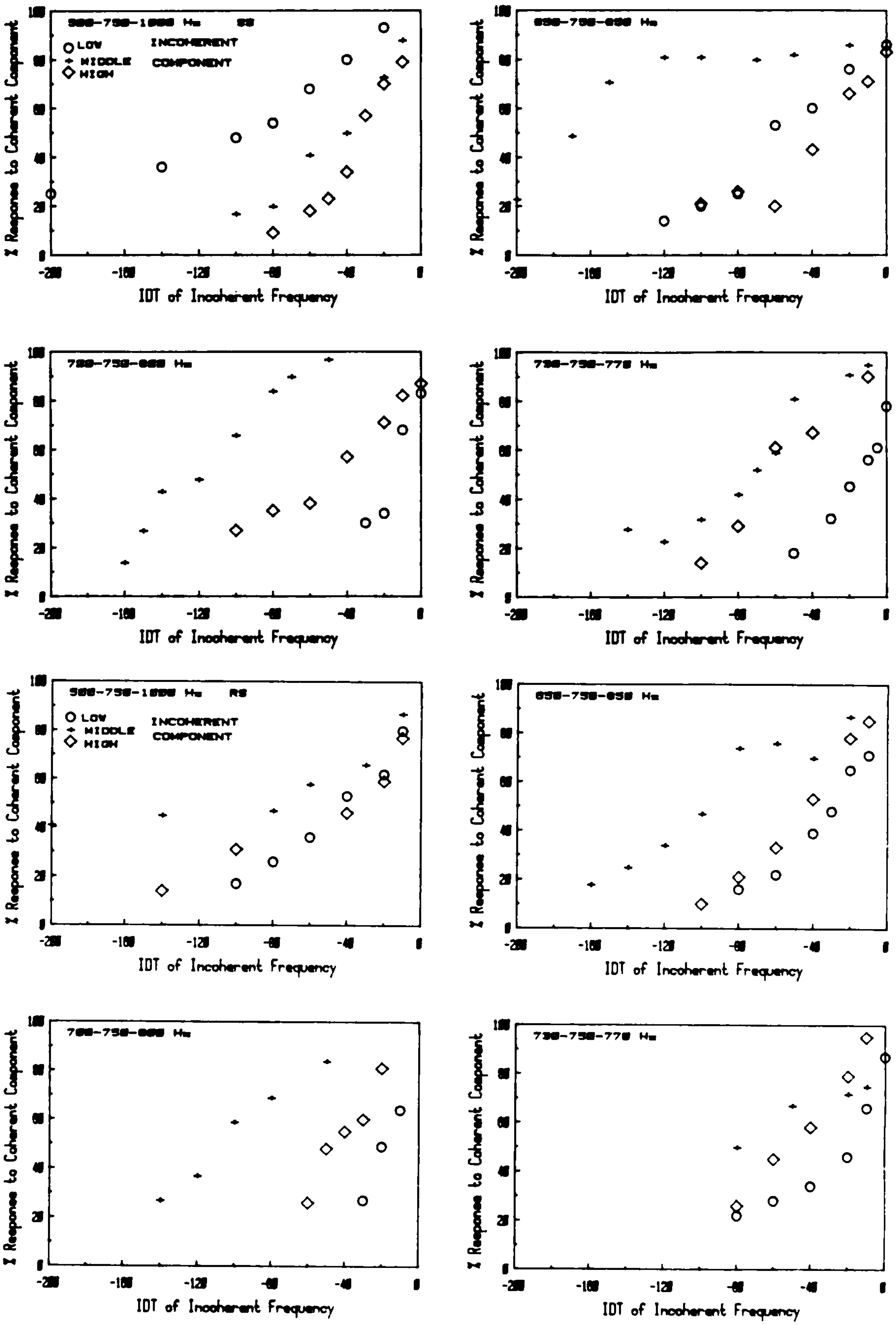
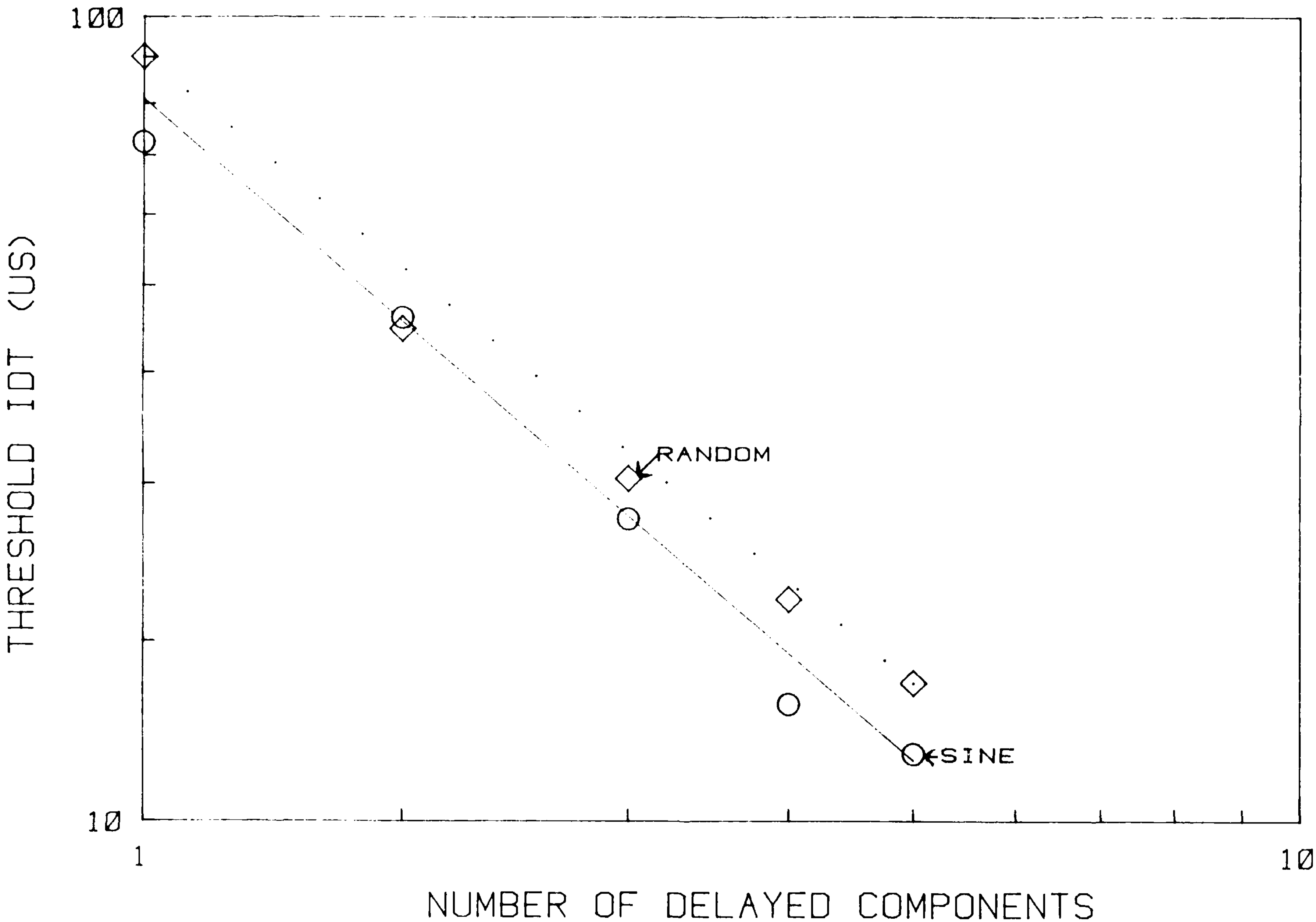

500-750-1000 Hz SS
LOW
MIDDLE
HIGH
INCOHERENT COMPONENT
650-750-850 Hz
700-750-800 Hz
730-750-770 Hz
500-750-1000 Hz RS
LOW
MIDDLE
HIGH
INCOHERENT COMPONENT
650-750-850 Hz
700-750-800 Hz
730-750-770 Hz
% Response to Coherent Component
IDT of Incoherent Frequency
0
20
40
60
80
100
-200
-160
-120
-80
-40
0

Fig 4



100
10
1
10
THRESHOLD IDT (US)
NUMBER OF DELAYED COMPONENTS
RANDOM
SINE

Fig 5

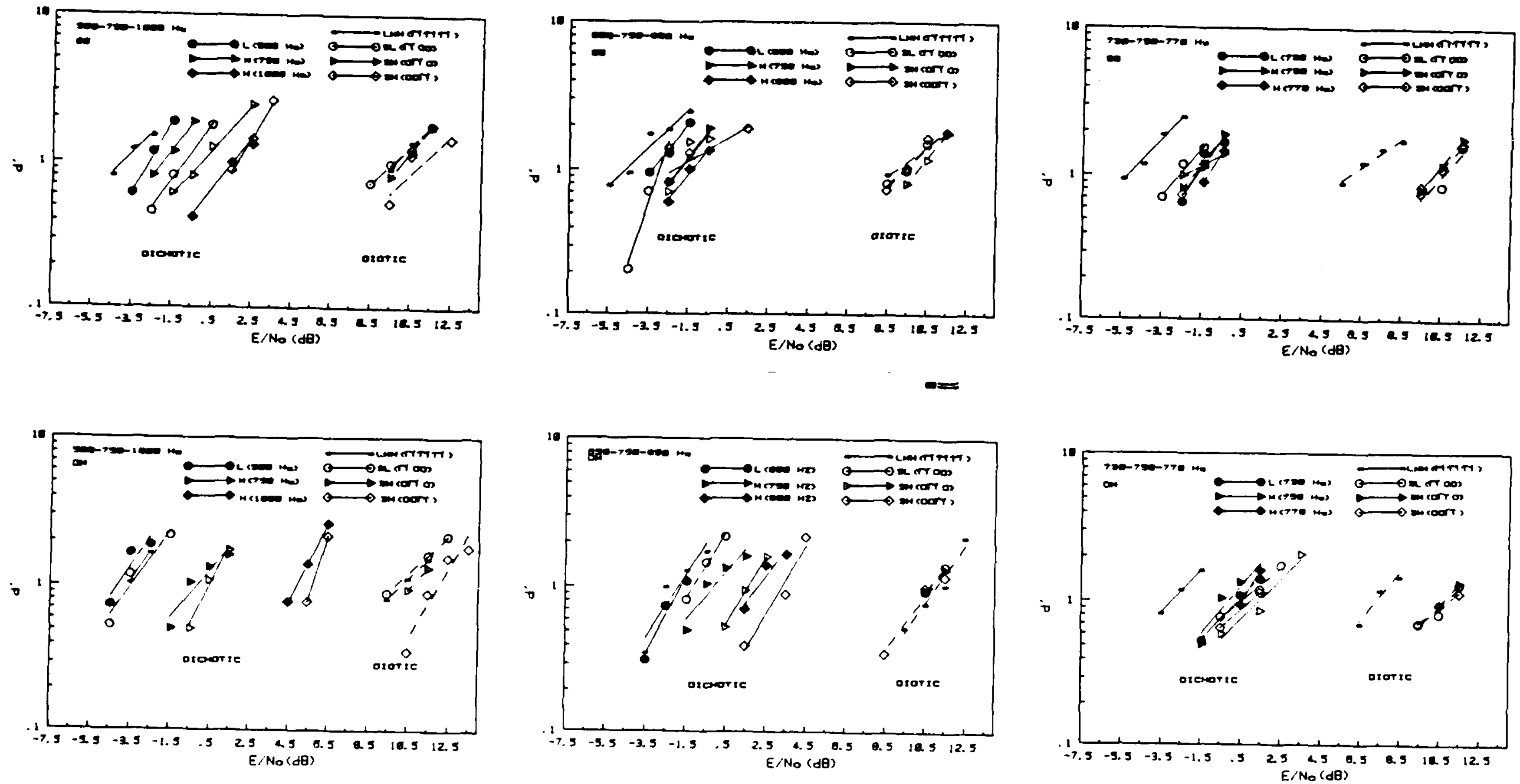
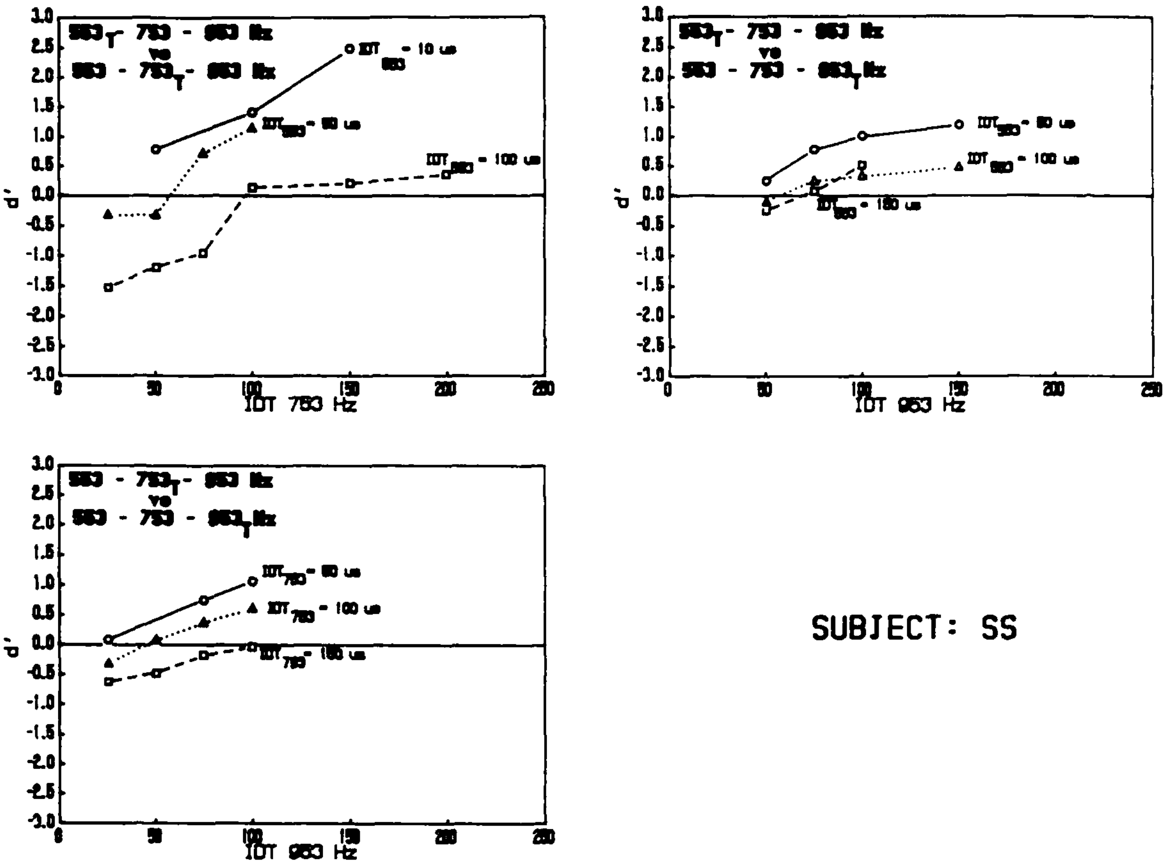


Fig 6



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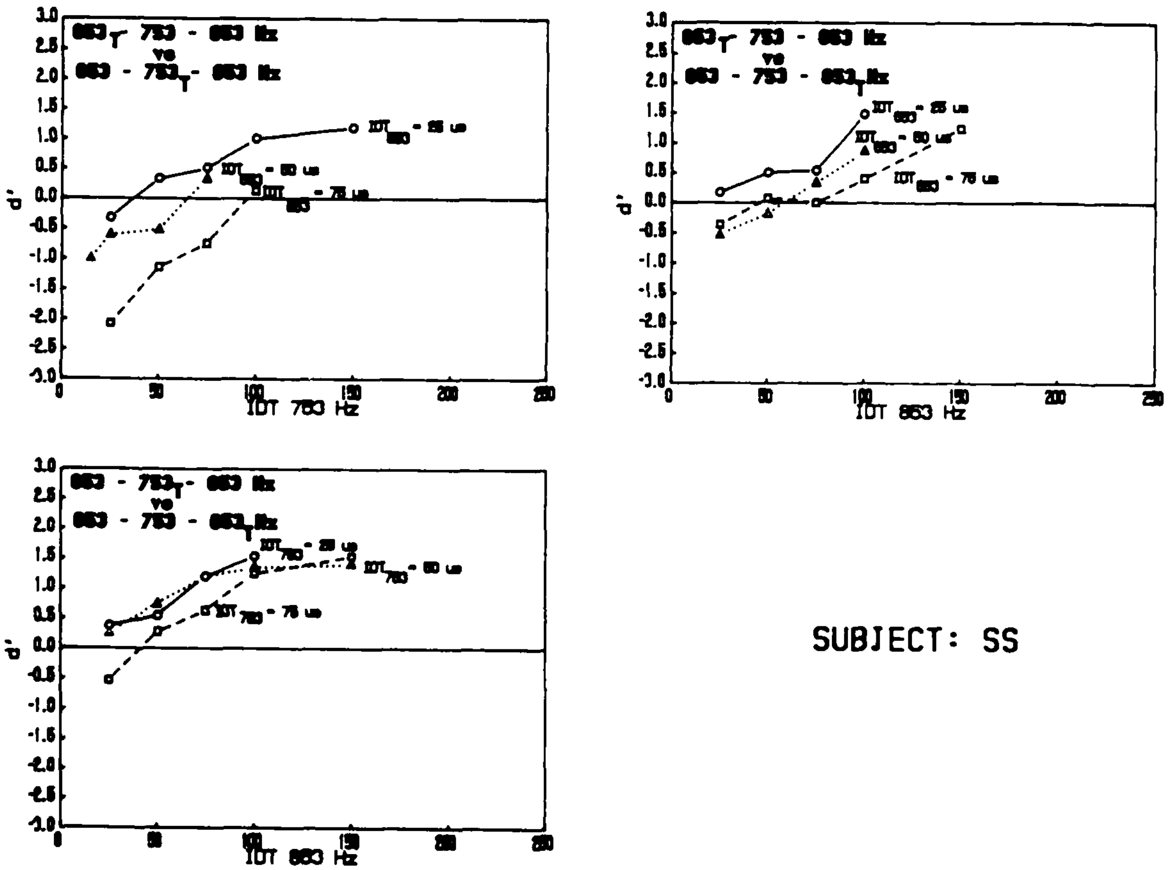

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